ANALYSIS OF SOLIDIFICATION AND REMELTING OF WATER OVER A CRYOCOOLED SPHERE THROUGH NATURAL CONVECTION

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ANALYSIS OF SOLIDIFICATION AND REMELTING OF WATER OVER A CRYOCOOLED SPHERE THROUGH NATURAL CONVECTION

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by

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Under the guidance of

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CERTIFICATE

This is to certify that the thesis entitled **Analysis of Solidification and Remelting of Water over a Cryocooled Sphere through Natural Convection**, submitted by **Vishnu Rajpuriya** to National Institute of Technology, Rourkela, is an authentic record of bonafide research work carried under my supervision and I consider it worthy of consideration for the award of the degree of Master's of Technology of the Institute.

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DECLARATION

I certify that

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2. The work has not been submitted to any other Institute for any degree or diploma.
3. I have followed the guidelines provided by the Institute in writing the thesis.
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We dream, we desire, we strive to achieve our dreams, at last it is our perseverance and determination that pays and then only we achieve what we dream. So, today it is my dream that I am at the meridian of achieving my goal. As I begin to write these lines; after completion of my thesis, my heart is filled with deepest sense of gratitude. I shall ever remain thankfully indebted to all those who have directly or indirectly encouraged me to achieve my goal and enlightened me with the touch of their cognizance and encouragement.

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Where emotions are involved words cease to mean, lexicon could not have the words to express the affection, blessings, encouragement, sacrifice and love of my beloved Mother, Father, Brother and Sister without which I would have never come to this proliferative stage and engaged myself in career building. Last and above all, having such a wonderful family that supports me whole heartedly, no matter what I do, is something I feel unique to my life. There are no words to pay regards to them for toiling so hard to bring me up to this stage. At last, I would like to express my deep sense of gratitude to almighty GOD, many known and unknown hands which pushed me forward.

Date :

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Place :

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LIST OF SYMBOLS AND ABBREVIATIONS

v_r	Radial velocity vector
v_z	Axial velocity vector
f_l	Liquid volume fraction
h_{sl}	Latent heat of fusion of water
k	Thermal conductivity
h	Enthalpy
μ	Viscosity of fluid
ν	Kinematic viscosity of fluid
D	Diameter of sphere
w_{max}	Maximum ice thickness
T_{total}	Total time

Greek symbols

α	Thermal diffusivity, $k/\rho c_p$
β	Co-efficient of thermal expansion
ρ	Density of fluid

ABSTRACT

The solidification of water by using cryocooled metallic sphere is studied both experimentally and numerically. In this experiment, the cryocooled metallic solid sphere is dipped inside the tank full of water. The experiment is performed with a steel ball having different diameters. The numerical analysis is also done and the result is compared with experimental result; a good match is obtained. The results are presented in terms of thickness of ice formed, time required for solidification and time required for melting. The flow field and heat transfer characteristics showed an axisymmetric feature indicating the flow to be laminar. However, it has been observed that the convection effect plays a major role during the melting process which results in an uneven melting of ice over the sphere.

Keywords: Cryocooled, Sphere, Solidification, Melting, Natural convection, Experimental analysis, Numerical modeling.

CHAPTER 1

Introduction

1.1 PCM(Phase Change Material)

A PCM is a material which use the latent heat of fusion for transferring the heat by changing the phase mostly from solid state to liquid state or vice versa. These PCMs are also named LHS System due to their high latent heat storing capacity within small variation in temperature. Different materials have different heat storing capacities.

1.1.1 Characteristics of PCM and its Classification

The LHS (latent heat storage) system of PCM's is achieved via solid to solid, solid to liquid, solid to gas and liquid to gas phase change. Mostly, solid-liquid phase changing property is used for phase change materials. Due to large variation in volume and high pressure liquid to gas PCM are not used for thermal storage system, because high pressure storage requires big heavy vessels. But Liquid to gas transitions are having higher latent heat value compared to solid to liquid state. And the solid to solid phase transformation is comparatively low and also have lower heat of transition.

Initially, the solid-liquid PCM absorbs sensible heat and temperature rises near to its melting temperature and at that instant the heat is absorbed but temperature remains nearly constant and this is the point when large amount of energy absorbed by material helps to change its phase to liquid. The characteristics of PCMs are as given below:

- Suitable Melting Point temperature.
- High melting enthalpy per unit volume.
- Specific heat must be high.
- Change in volume must be less due to change in phase.
- Its thermal conductivity must be high.
- It must not be corrosive chemically.
- It must not be poisonous.
- It must be non-flammable.

A number of PCMs are normally available for preferred temperature range i.e $-10°C$ to $190°C$. Also it must be in range of the human comfort zone i.e 20–30$°C$. Many of the PCMs are very effective as they are capable of storing 5-14 times heat energy per unit volume of PCMs than conventional phase change storage materials such as water. The classification of phase change material are as follows:

1.

   Organic PCMs : example: (1) Paraffin wax (C_nH_{2n+2}) and fatty acids ($CH_3(CH_2)_{2n}COOH$) etc.

   (a) Advantages of Organic PCMs are:

   - It freezes with less supercooling.
   - It has ability to congruently melt.

- It is compatible with the conventional material.
- Generally no segregation is seen.
- It is chemically stable.
- It has heat of fusion very high and is safe.

(b) Disadvantages of Organic PCMs:

- In solid state it is having lower thermal conductivity.
- In freezing cycle, heat transfer rates are higher.
- Latent heat storing capacity is higher per unit volume.
- Less flammable property.

2. Inorganic PCMs : example: Salt hydrates (MnH_2O)

(a) Advantages of Inorganic PCMs are:

- Latent heat storing capacity is higher per unit volume.
- Easily availabile and has lower cost.
- Thermal conductivity is higher.
- Heat of fusion is comparitively high.
- Non-flammable chemically.

(b) Disadvantages of Inorganic PCMs are:

- Volumetrics variation is very high.
- Supercooling is one of the major problem in solid-liquid transition.

3.

Eutectics PCMs:

(a) Advantages of Eutectics PCMs :

- It is having sharp melting point same as of pure material.

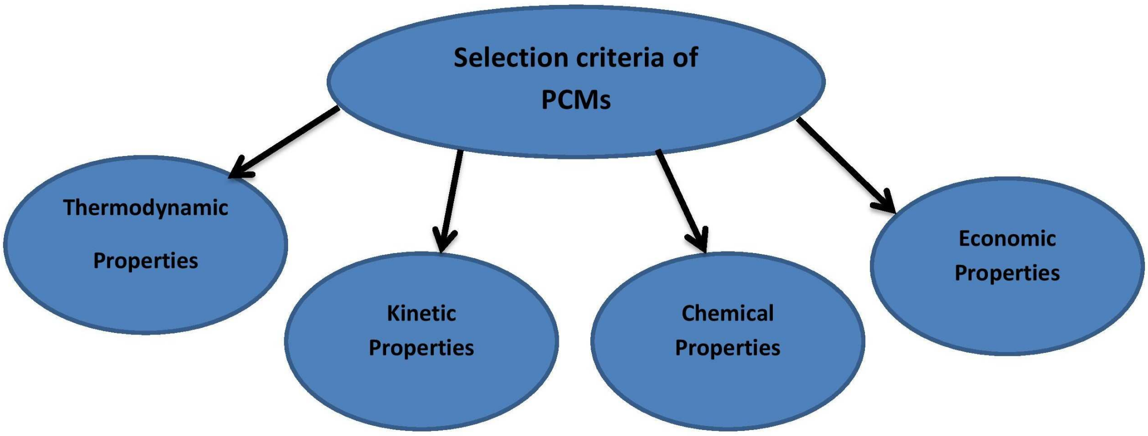


Figure 1.1: Flow chart showing selection criteria of PCMs

- Volumetric storage is little above organic compounds.

(b) Disadvantages of Eutectics PCMs are :

- Very less data is available.

4.

Hygroscopic materials:

(a) Many building materials are hygroscopic by nature i.e. they can absorb and release water.

1.1.2 Selecting Criteria

The selection of the PCM depends on the area where it is used. Parameters taken in consideration are shown in figure 1.1.

1. Thermodynamic property.

   - The required melting temperature must be according to the different range of temperatures.

- The latent heat of fusion per unit volume should be higher.
- They should have higher specific heat at constant volume.
- Density and thermal conductivity should be higher.
- the change in volume must be less during phase transformation.
- congruent melting.

2. Kinetic Properties

    - To avoid supercooling in liquid state, They must have high nucleation rate.
    - It must be having higher crystal growth rate.

3. Chemical Properties

    - It must be chemically stable.
    - It must have reversible freeze/melt cycle.
    - It must not degrade after number of cycles.
    - It must be non corrosive and non flammable.
    - It must not explode while working in defined conditions.

4. Economic Properties

    - It must have be cheaper.
    - it must be easily available.

1.1.3 Development of PCM

For last 2000 years water is being used as PCM used because it possesses very high latent heat and also good thermal conductivity. The only drawback of water was its volume increases 2.2% when freezes and expands 1330 times after $10.0^{o}C$ of evaporation at atmospheric pressure. Due to this, water is not used in small latent heat storage system. After this number of PCM are developed having less volumetric expansion during phase

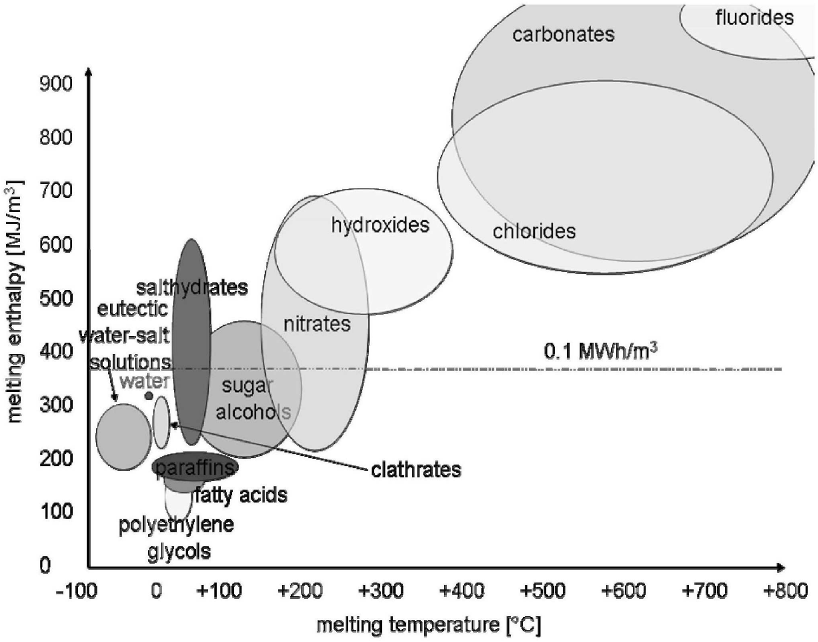


Figure 1.2: Classification of materials used as PCM with their range of melting temperature and melting enthalpy (Bavarian Center for Applied Energy Research)

change. The PCMs are produced on basis of area to be used, which makes them more reliable and efficient. Figure 1.2 has been taken from 'Bavarian Center for Applied Energy Research' which shows different PCMs. It shows the PCMs commonly used on basis of temperature range and required melting enthalpy.

1.1.4 Applications

The application of PCMs are:

- In Thermal energy storage systems.
- Air conditioning of the buildings.
- In storage of ice.
- Maintaining temperature of heat engines and electrical devices.
- Preservation of food items, beverages, milk-products.
- In medical, i.e. blood preservation, maintaining operation theatre.

Material	Melting Temperature (^oC)	Heat of Fusion $kJ.kg^{-1}.K^{-1}$	Specific heat, (c_p) $kJ.kg^{-1}.K^{-1}$(solid)
Water	0	333.6	2.05
Density,(ρ) $kg.m^{-3}$ (solid)	Density,(ρ) $kg.m^{-3}$(liquid)	Thermal Conductivity (k) $W.m^{-1}.K^{-1}$	Specific heat, (c_p) $KJ.kg^{-1}.K^{-1}$(liquid)
917	1,000	0.6 - 2.22	4.186

Table 1.1: Properties of Water

- Conditioning of human body to keep in comfort zone.
- Cooling of heat pump systems.
- Storage within bio-climatic building.
- In solar thermal power plant cooling.
- Space shuttle thermal cooling systems.
- Thermal comfort in vehicles.
- Protection of the electronic devices from heating.
- It is used in computer cooling.
- It is used in turbine inlet cooling with TES (thermal energy storage).
- As Fire extinguisher, Water based non-toxic, non-flammable PCMs are used. Many of the PCMs are organic and are also flammable.

1.2 Solidification and Melting of Water

Table 1.1 shows the thermophysical properties of water which is the most commonly used PCM. The solidification and melting of water is shown in figure 1.3. During heating, the water firstly absorbs sensible heat until it reaches the latent heat of vaporization. At this point, the temperature remains constant and heat is absorbed until the phase gets changed. As the phase change is completed the temperature again starts rising up along with heat addition. Similarly in freezing, water rejects the sensible heat until it

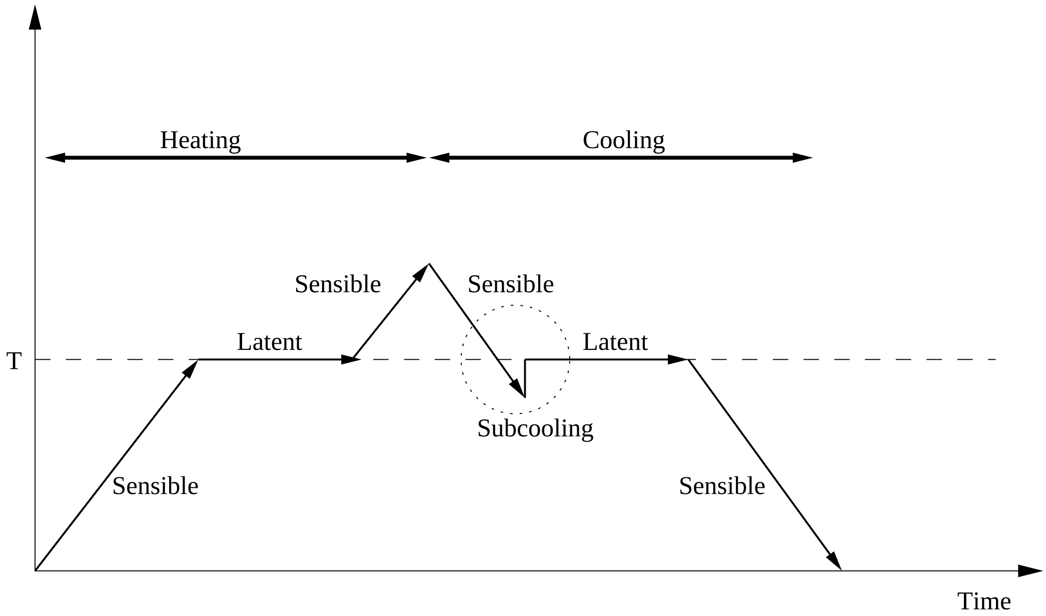


Figure 1.3: Variation in temperature during heating i.e melting and cooling i.e. solidification of a water

reaches its freezing temperature and at this point its temperature remain constant and it rejects it latent heat of fusion causing change in phase to solid i.e. ice. At this stage, the temperature goes to sub cooling region until all the volume of water changes to ice and then again the temperature returns to freezing temperature.

1.3 Encapsulation of PCMs.

1.3.1 Encapsulation of PCMs:

The PCMs used now-a-days are stored inside cylindrical tanks, rectangular tanks, using fins, plates or spherical capsules. Studies of PCM on all these structures are preceding from decades. Recently, spherical encapsulation is preferred over other structures because of its higher heat transfer area in relation with volume of energy stored. It gets easily loaded in storage tank, effectively generating better porous bed.

1.3.2 Requirements for the PCM containers

PCM encapsulation must fulfill following criteria:

1. High strength, flexibility.
2. Must have corrosion resistance and thermally stable.
3. It must have enough surface area for the transfer of heat.
4. It must be stable mechanically and must be easy to carry.

1.4 Review of Literature

The first study of freezing was done by Stephan in 1891. He studied freezing phenomena in one dimensional steady state condition. He considered some assumption i.e. the temperature gradient at liquid phase is zero and heat flux across the solid is constant. We are basically focusing on the effect of ice formation through natural convection which was first studied by Riley et al. [1], he studied solidification of PCMs inside the sphere and cylinder through sudden chilling them externally and which resulted in constant thermal properties including certain parameters. Cheng et al. [2], experimentally studied the ice formation around cylinder in cross-flow and it was performed under temperature range 6.3^{o}C to 75.8^{o}C and found out local heat transfer coefficient, ice profile by using Laplace equation. As this research work was getting its new aspects . Moore and Bayazitoglu [3] prepared a mathematical model and found the energy storage characteristics and convective effects due to melting within spherical enclosed cavity. Hartnett and Minkowycz [4] did experiment of freezing of super-heated water around isothermal horizontal cylinder and used shadow graph technique to visualize plume development and photographically recorded the contour formed. Again,Cheng et al. [5] studied the ice formation around horizontal cylinder by dipping inside a steady water bathe at ambient temperature and found the Nusselt number and the average Nusselt number behavior at stagnation point etc. Later in 90's, Saito et al. [6] experimentally and statistically analyzed supercooling phenomenon on heat transferring surfaces explaining that freezing is effected by characteristics of surfaces and cooling condition concluding plot of probability of freezing from the super cooling state and freezing temperature for respective surfaces. Chen et al. [7] studied the density inversion effect of water and found the shape of ice layer, flow pattern correlation between Nusselt number and Modified Grashoff number. Fukusako and Yamada [8] researched on varieties of water freezing and ice melting problems and represented effects like decrements in flow rate, hydraulic pressure loss, and damage caused by blockage due to ice formation in pipes. These experiments were further carried out on immiscible fluids, Yamada et al. [9, 10] immersed cylinders inside immiscible fluid, i.e. vegetable oil. The experiment was carried out with hot and cold tube which had respective temperature of 8.0^oC to 30^oC and-5.0^oC to-13.0^oC and later they did the experiment by immersing vertical ice cylinder. The shape was one of the main aspect for heat transfer so, different shapes came into existence such as sphere. li Chen and shing Lee [11], Chen et al. [12] studied about supercooling and freezing inside a cylinder placed horizontally. They have studied the effect of cooling rate, internal diameters of cylinders. Further they carried out experiment on different types of nucleation agents that are silver iodide (AgI), lead iodide (PbI_2) and concluded that nucleation was increased by Silver Iodide more than any other material.

Ismail and Padilha [13], Ismail and Henriquez [14], Ismail et al. [15] studied transient ice formation in rectangular duct by converting all basic transient equation into dimensionless form and transformation to steady state condition. Ismail performed numerical analysis of ice formation inside spherical capsule and used governing equations which was solved and compared with the results provided by different author and was used to determine size ,initial temperature of material used, outside temperature and solidification time etc.. Yoon et al. [16] experimentally studied water freezing at supercooled horizontal cylinder and they used holographic real time interferometry technique and showed freezing pattern at different cooling rates described shape of crystals at higher and lower cooling rates. All the studies done for cylinders were in the short cylinders but there was actual problem arising with cylinder was that there were long cylinder used in transportation of PCM and other temperature sensitive materials, so a proper study and analysis was required for long cylinder. Khodadadi and Zhang [17] did computational study on the effect of buoyancy inside spherical container using iterative, finite volume method. They noted that Prandtl number plays an effective role in melting process and even flow is different with melting pattern. Okawa et al. [18, 19] studied solidification phenomenon of water containing some solid particles (Silver Iodide) along with contaminants and found relationship between degree of super cooling. Later on, freezing on metallic surface (Gold plated, Copper plated) with different cooling rates is studied by them and they concluded that probability of freezing was independent of cooling rates. Omari and Dumas [20] numerically studied about spherical nodules inside cylindrical tank (2500nodules/m2) while cooling from outside and analyzed with CFD simulation for finding influence of natural convection Cheralathan et al. [21] modeled CTES (Cool Thermal Energy Storage) which consists of ethylene glycol chiller and compared results with experimental values of other authors and concluded that increase in porosity contributes higher rate of energy storage and mass of PCM charged decreased as porosity increases.Habeebullah [22] experimentally studied ice formation around horizontal long cylinder made of copper, He did his experiments in isolated vessel and found a sudden increase in the thickness of ice formed at bends. This feature was observed only for Reynolds number =251.9 and Biot number < 1, but this was not same for higher Reynolds number. Later, the number of cylinders were considered because the amount of heat transfer will increase as the surface area will increase, Kalaiselvam et al. [23] experimentally as well analytically studied characteristics of PCM inside cylinder finding location of interface at different time, they also considered internal heat generation which increase the total solidification time by increasing the melting rate. Buyruk et al. [24] investigated for ice formation around various cylinder kept inside ice storage tank filled with water. They used software package “FLUENT” for analysis of data and found the temperature distribution, liquid fraction and ratio of area. Erek and Dincer [25] analyzed heat transfer behavior of enclosed Ice TES using different diameter of capsule mass flow rates, temperature of fluid used and solidification process is dependent upon Stephan number, diameter of capsule. Tan et al. [26] experimented and computationally investigated the buoyancy effect on convection inside spherical capsule. Using CFD Fluent they compared the experimental results and showed that at top of the sphere the molten liquid layer is stable but as we move towards bottom of sphere this stability starts deviating. Ezan et al. [27] studied the importance of natural convection during ice formation in rectangular section and analysed the results with previous experimental values and concluded that during phase change process natural convection has turbid effect.

Beside all these studies, The literature survey reveals that most of the studies are limited to cylindrical geometries. However, very few considered the spherical geometries. As we know that sphere is more effective than cylinders and any other geometries so in this study, freezing of water is considered over the surface of an isothermally cryocooled sphere. The study is performed through experiments and modeling on steel sphere of different sizes. The results are presented in terms of time of solidification, time of melting and the thickness of ice formed at different axial locations, correlations between different dimensionless quantities . Overall solidification and melting of ice are discussed in details.

1.5 Outline of the thesis

Development of a heat transfer model for parametric studies on laser tissue interactions is the main work of this thesis. This thesis consists of three chapters. A short description of each chapter is given below.

Chapter 1: This chapter consists of general introduction of PCM, its classification, usage of PCM with different condition, developments which are done and still in process and its application.

Chapter 2: An experimental analysis of freezing of water over a cryocooled sphere is studied and also the numerical modeling has been done whose results are validated with experimental results. The study of ice thickness formed was analyzed experimentally and numerical results obtained are almost matched. The flow field and velocity of fluid due to natural convection is visualized through photographs, videos etc. Relation between the Time and ice thickness along different portion i.e

Top, Bottom, Center is achieved non dimensionally. And also the Radius of sphere and ice thickness is analysed during different time instances.

Chapter 3: Findings and future work.

CHAPTER 2

Experimental and Numerical Analysis of Water

2.1 Experimental work and methodology

2.1.1 Setup and material required

In this experimental setup as shown in figure 2.1 water tank of $30cm \times 30cm \times 30cm$ dimension was made by Acyrilic Sheet (Poly methyl methacrylate) or PMMA which is having very high transparency and is $5mm$ thick. Steel sphere of three different standard diameter i.e $4.14cm$, $3.18cm$ and $2.72cm$ is used. For lifting up the sphere ball and dipping it inside the liquid nitrogen container, a net made of high density polyethylene (HDPE) is used and which was tied by string made up of high-modulus Vectran fiber. A wooden ply is used for carving out frame which supports the water tank as well as for hanging the steel sphere and a pin has been hooked to top-center of wooden frame, where string can be tied easily within 2 seconds. A high resolution camera, Sony Cyber-shot WX 350, is used for visualization of solidification and melting processes which is kept facing the water tank. A LED light is also fixed for proper visualization.

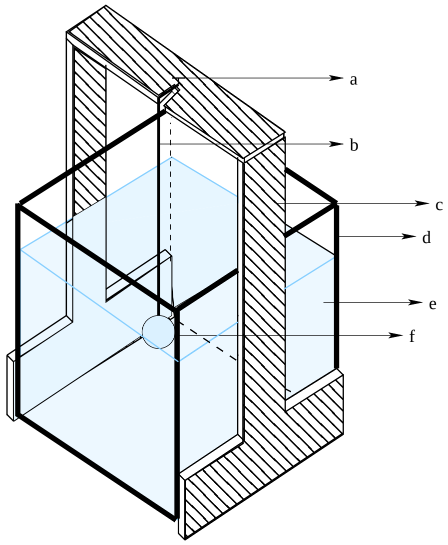


Figure 2.1: Experimental setup (a)Holding pin, (b)Polymer string, (c)Wooden frame, (d)Acrylic tank, (e)Water, (f)Metal sphere

2.1.2 Operating condition

The experiment was performed under normal room temperature at 20^oC. At initial condition the temperature of steel sphere was 20^oC. A small liquid nitrogen container which was full of liquid nitrogen at -196^oC and water inside the acrylic tank was at 20^oC.

2.1.3 Procedure

In this experiment, first of all the solid steel sphere is dipped inside the liquid Nitrogen container. Usually 8 to 10 minutes are required for steel sphere to reach the liquid nitrogen temperature. During this time there is boiling of liquid nitrogen, which is in contact with the surface of metal ball. Ultimately, the boiling stops once the equilibrium condition is reached. As this temperature is reached it is lifted up by the string tied with the net and is dipped inside the water tank as soon as possible with minimal vibration.These all processes are done manually with hands. After this, the freezing and thawing process takes place and as the meting process is completed, the ball is again lifted up and is allowed to dry and attain the room temperature. In this way a single experiment is completed and the same procedure is repeated with other sizes. Video and images of the solidification and melting process have been captured at different time instants.

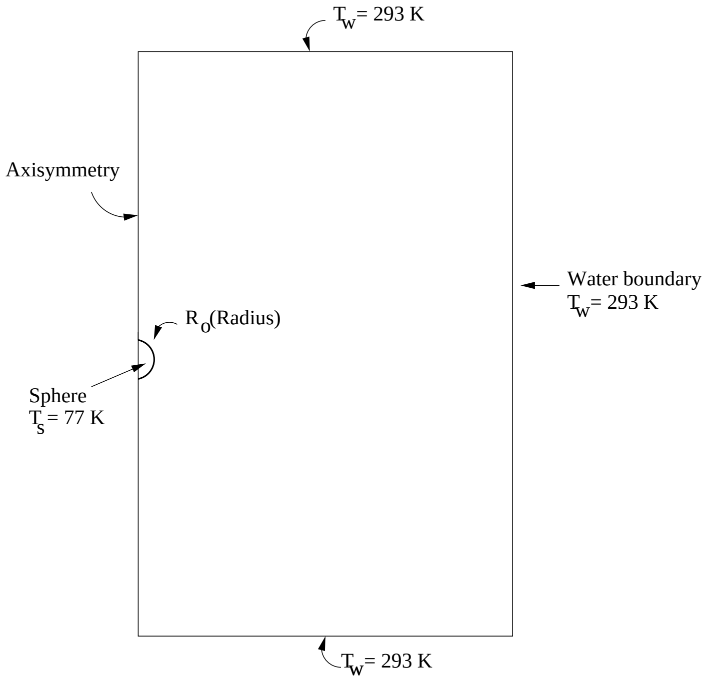


Figure 2.2: Schematic diagram of metal sphere and surrounding water

2.2 Numerical modeling

2.2.1 Governing differential equation

Figure 2.2 shows the axisymmetric spherical steel ball which is at liquid nitrogen temperature, i.e -192^oC. The 41.4 mm, 31.8mm and 27.2mm diameter steel balls are considered for the experiments. The initial temperature of water is 20^oC and the far away boundary is taken at an axial and the radial location of 40 times the radius of the steel sphere. Laminar and axisymmetric flow of the Newtonian and also incompressible fluid are considered. The 2d axisymmetric Navier-Stokes equations along with energy transport equation are presented as follows:

$$\nabla \cdot \left(\rho \mathbf{v}\right) = 0 \tag{2.1}$$

$$\rho \frac{\partial v_r}{\partial t} + \left(\rho \mathbf{v}\right) \cdot \nabla v_r = -\frac{\partial p}{\partial r} + \nabla \cdot \left(\nabla \left(\mu v_r\right)\right) - \mu \frac{v_r}{r^2} + A v_r \tag{2.2}$$

$$\rho \frac{\partial v_z}{\partial t} + \left(\rho \mathbf{v}\right) \cdot \nabla v_z = -\frac{\partial p}{\partial z} + \nabla \cdot \left(\nabla \left(\mu v_z\right)\right) + A v_z \tag{2.3}$$

$$\rho \frac{\partial h}{\partial t} + \left(\rho \mathbf{v}\right) \cdot \nabla h = \nabla \cdot \left(\frac{k}{c_p} \nabla T\right) - \rho \Delta h_{sl} \left(\frac{\partial f_l}{\partial \tau} + (\mathbf{v} \cdot \nabla) f_l\right) \tag{2.4}$$

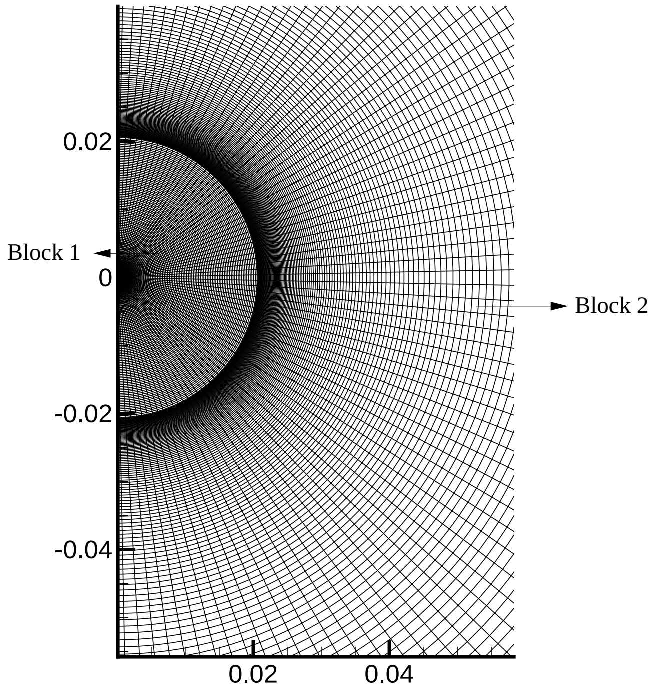


Figure 2.3: 2-dimensional computational grid of sphere and water

In the above equations v_r and v_z are the radial and the axial components of the velocity vector, f_l is the liquid volume fraction, and Δh_{sl} is the latent heat of fusion of water. In the energy equation (2.4), the left hand side represents transient component and convective heat transfer component, first term on the right hand side represents diffusion and the second term represents heat sink/source due to solidification/remelting at the phase change interface around the steel ball.

To solve the energy equation, a single region (or continuum) enthalpy formulation is implemented. A Darcy law type porous medium formulation, due to [28], is utilized to account for the effect of phase change on convection. The last term in the momentum equations (2.2) and (2.3) is the Darcy damping term which set the solid velocity equal to zero as the coefficient A becomes very large.

2.2.2 Solution Approach

The two-dimensional axisymmetric Navier-Stokes equation along with energy equation have been discretised on a structured collocated, non-orthogonal multiblock grid system using finite volume approach. The grid with two structured blocks used for this simulation is shown in figure 2.3. The governing equations were solved using SIMPLE algorithm of [29]. The computational domain size used depends not only on the size of the sphere but also on the condition to which the sphere is exposed. As we are also solving the case of pure conduction; to impose the free stream boundary conditions, far stream distances are taken equal to forty times the radius of the steel ball. A multiblock grid system having two blocks of 80×80 and 80×200 was found to be sufficient to resolve the details of flow, temperature fields and the liquid-solid interface positions. The first block corresponds to the grid system used for steel ball while second one is used for meshing the entire water domain. The temporal discretisation was done using implicit three time level scheme. Detailed discussion about the structured multiblock system adopted here can be found in [30].

2.2.3 Grid Independency Test

Before going for the productive runs, the developed code is also tested for grid independency. Figure 2.4 shows the average ice thickness variation with time for the sphere diameter of 41.4 mm. The figure shows the results obtained with three sets of grid densities; the coarse grid, fine grid, and finest grid containing 70×70 and 70×210, 80×80 and 80×240, and 90×90 and 90×270 control volumes within block 1 and block 2 respectively. Block 1 refers to the grid density inside the solid sphere and block 2 to the surrounding water. It can be noticed that the variation between the solutions obtained with coarse grid and the fine grid is large while this variation almost becomes negligible after comparing the solutions obtained with fine and finest grids. This indicates a grid independent solution is obtained with the fine grid distribution. And, therefore, grid distribution corresponding to the fine grid is adopted for the entire simulations.

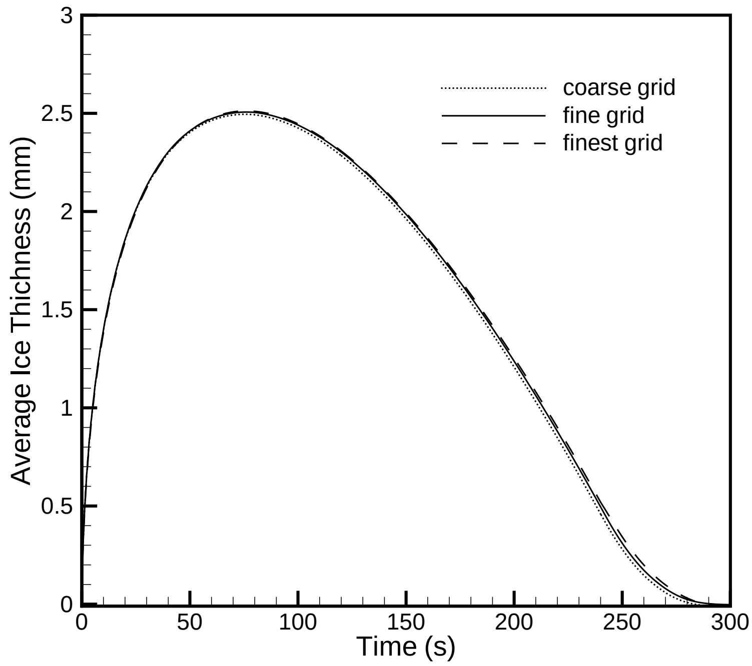


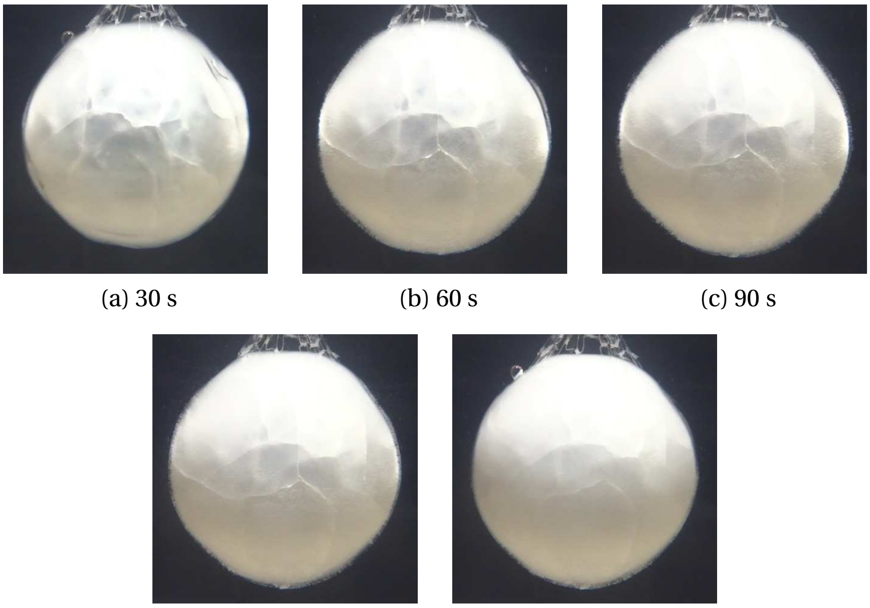
Figure 2.4: Grid independence test

2.3 Results and Discussion

2.3.1 Experimental Results

The experiment is performed number of times with three different sizes of steel balls and the picture is taken at different time instant during solidification and remelting of ice. As steel ball is cooled to the liquid nitrogen temperature and then dipped inside the water tank, freezing of water starts instantly. More or less the solidification is mostly governed by the diffusion process which reflects in almost spherical layer of ice thickness over the steel sphere; as can be seen in figure 2.5. The effect of convection is very less. However, during melting process, convection effect dominates which results in an uneven melting of ice layer which is also reflected in figure 2.6.

When solidification starts, the water in contact with sphere starts loosing its sensible heat and latent heat within fraction of seconds and starts freezing. Due to convective effect uneven solidification starts, this unevenness can be seen in figure 2.5(a) which is taken at 30s of the solidification process. There are small bulging which is vis-

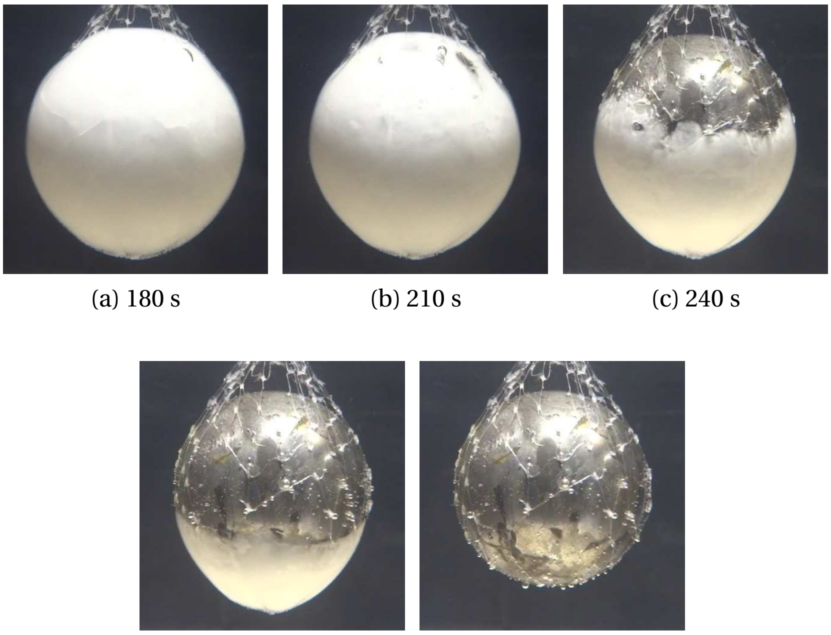


(a) 30 s (b) 60 s (c) 90 s

(d) 120 s (e) 150 s

Figure 2.5: Solidification of water of 4.14 cm diameter sphere

ible with naked eyes along with small cracks which is caused due to extreme cooling of ice formed on surface. As temperature is nearly equal to the liquid nitrogen temperature i.e.-192^oC, the ice formed at 0^oC tries to attain temperature of liquid nitrogen. Due to this, ice starts contracting which results in cracking. With the passage of time ice thickness increases as we can see in the figure 2.5(b). The ice thickness keeps on increasing during solidification process as it can be seen in figure 2.5(c) and 2.5(d). At t = 120s the solidification process is almost completed. The solidification is mainly governed by the diffusion process which reflects in almost spherical ice layer. After this the melting starts. Due to natural convection heat transfer melting process starts unevenly which is reflected by spheroidal shape of the frozen ice. For this case, the buoyancy takes place from top to bottom, causing top surface to melt faster compared to the bottom surface. That is why bottom surface of sphere is having more ice thickness as we can see in figure2.6(b) and at this time the melting is more pronounced near the top part of sphere, this is due to buoyancy-driven convection which has been explained by [26]. This can be observed in figures 2.6(c),(d) and (e).



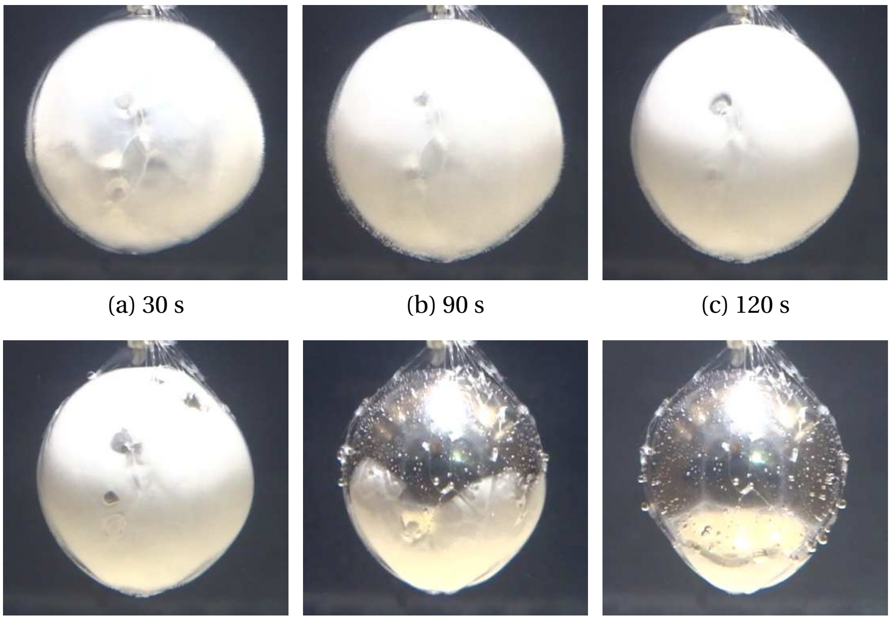
(a) 180 s (b) 210 s (c) 240 s

(d) 270 s (e) 305 s

Figure 2.6: Melting of ice of 4.14 cm diameter sphere

Time(s)	Thickness on Top(mm)	Thickness at Center(mm)	Thickness at Bottom(mm)
60	1.5	2.5	3
120	0.2	1	3
131	0	0.5	2.85
144	0	0	2.65
180	0	0	0

Table 2.1: Ice thickness at different position for 2.72cm diameter steel sphere

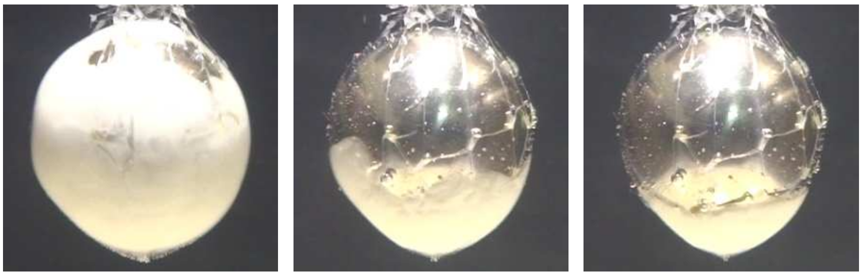


(a) 30 s (b) 90 s (c) 120 s

(d) 150 s (e) 180 s (f) 200 s

Figure 2.7: Solidification and remelting of water for 3.18 cm diameter sphere

(a) 30 s (b) 60 s (c) 90 s



(d) 120 s (e) 150 s (f) 160 s

Figure 2.8: Solidification and remelting of water for 2.72 cm diameter sphere

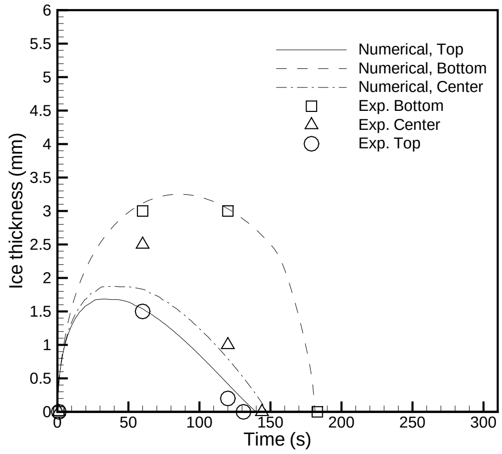
Time(s)	Thickness on Top(mm)	Thickness at Center(mm)	Thickness at Bottom(mm)
60	2.5	3	4
120	2.5	2.9	4.8
180	1.5	1.8	4.5
235	0	0.6	3.4
257	0	0	3.1
305	0	0	0

Table 2.2: Average ice thickness at different position for 4.14 cm diameter steel sphere

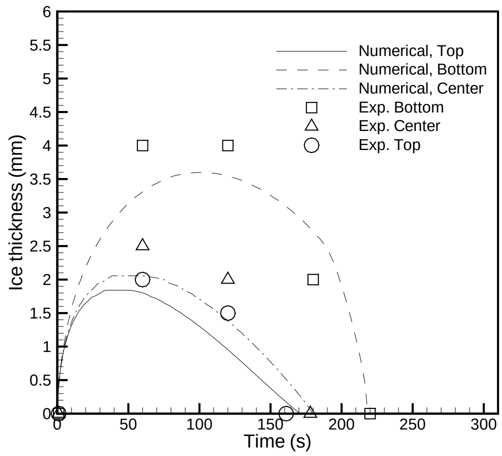
2.3.1.1 Observation table and Calculation

The table 2.2, 2.3, 2.1 show thickness of ice layer formed and remelted at top, center and bottom of spheres having diameters of 4.14 cm, 3.18 cm and 2.72 cm. From the data, one can observe that the bottom part of sphere is having more amount of ice formed and also during melting, due to buoyancy driven convection, it take longer time to melt completely compared to the other parts, i.e top and center. A graph is plotted for the evolution and destruction of ice layer with time during solidification and melting processes respectively in figure 2.9 for all the studied cases. From the graph, it is clear that the trend followed up by ice thickness is same for each of the sphere.

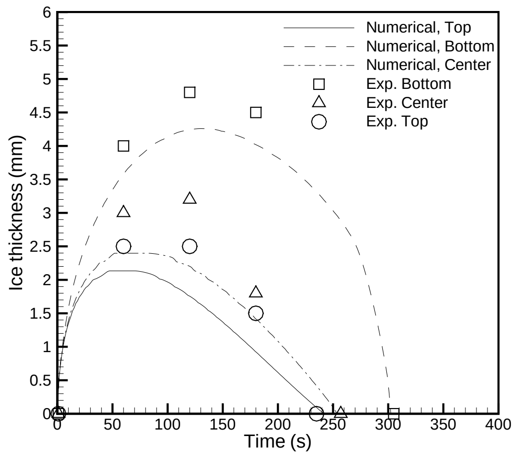
As we can see in figure 2.9 (a) which is for 2.72 cm diameter sphere, top portion of sphere is having least ice thickness formed and also for shortest time and as we move



(a) Ice thickness at different position around 2.72 cm diameter sphere



(b) Ice thickness at different position around 3.18 cm diameter sphere



(c) Ice thickness at different position around 4.14 cm diameter sphere

Figure 2.9: Graph showing solidification and remelting of water for different sizes of sphere

Time(s)	Thickness on Top(mm)	Thickness at Center(mm)	Thickness at Bottom(mm)
60	2	2.5	4
120	1.5	2	4
161	0	0.5	2.5
178	0	0	2.2
180	0	0	2
220	0	0	0

Table 2.3: Average ice thickness at different position for 3.18 cm diameter steel sphere

Non dim. time	Non dim.Average thickness (4.14 cm)	Non dim. Average thickness (3.18 cm)	Non dim. thickness (2.72cm)
0	0	0	0
0.10	0.805	0.80	0.744
0.25	1	1	1
0.5	0.883	0.91	0.948
0.75	0.453	0.54	0.51
1	0	0	0

Table 2.4: Non dimensionalised time and average thickness

towards the bottom side, the ice thickness increases and time for which ice layer sustain increases. This happens due to buoyancy driven convection. Due to this the bottom part as we can see, is having most thickness of ice layer formed and it is sustaining for longest time. Similarly other spheres in figure 2.9 (b) and (c) shows common results when compared with the numerical results. Very small variation is observed which can due to human errors and atmospheric condition but it is negligible. The trend followed up by experimental results are similar to the numerical modeling result. Form bottom part, it is easy to recognize the total solidification time and melting time of ice formed for any different size of spheres.

Figure 2.10 depicts the variation of nondimensionalised average thickness of ice with the non-dimensional time.The thickness is normalized with respect to the maximum average thickness of ice for the respective case and time is normalized with respect to the total time of the process, i.e. solidification time plus the melting time. This figure is plotted just to see the effect of sphere size on the heat transfer characteristics. And, to our surprise, all the three curves collapsed into a single one indicating almost similar heat transfer characteristics for all the cases. The figure also depicts a more steeper curve for solidification process as compared to the melting process. This indicates that solidification of water takes less time than melting process. The reason being the high temperature difference in the beginning of the process which results in a rapid solidification. The temperature difference decreases with the passage of time resulting in longer time of melting.

The table 2.4 shows data extracted for three different sizes of sphere i.e Nondimensionalised time vs Non-dimensionalised thickness. This has been plotted in figure where it is clear that the solidification and melting process of sphere same material irrespective of sizes proceed in same path. Their might be little variation in the results due to atmospheric condition, purity of water, some human errors. then also we are having approximately good results. In figure 2.10 the solidification curve is more steeper which says that solidification of water takes very less time as the temperature is very less i.e $-192^{o}C$ the rate of cooling is more. At non-dimensional time 0.25 to 0.5 the thickness of ice layer remain constant this is due heat transfer through the ice is almost constant or we can say that the change in temperature is almost zero for few instants of time. After this the slope of curve is less steeper which tell the melting of ice is occuring slowing and also the time taken is more than solidification time.

Non dim. Radius	Non dim. Average thickness at 0.25	Non dim. Average thickness at 0.5	Non dim. Average thickness at 0.75	Non dim. Average thickness at 1
0	0	0	0	0
0.52	0.769	0.767	0.75	0
0.77	0.8722	0.8752	0.88	0
1	1	1	1	0

Table 2.5: Nondimensionalised radius and average thickness at different non dimensionalised time.

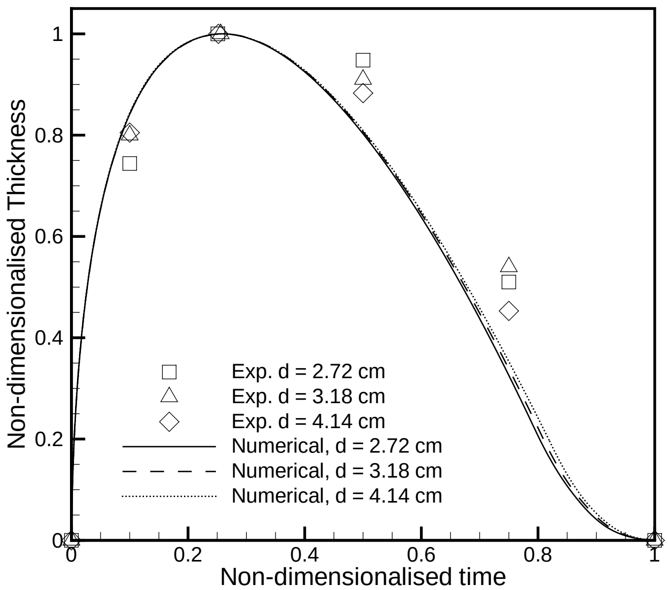


Figure 2.10: Graph showing non dimensionalised solidification and remelting of water around spheres of different diameter

The table 2.5 shows the relation between the radius of sphere and ice thickness formed at different time aspects in nondimensionalised form. The figure 2.11 shows the data above graphically, here the increase in thickness of ice is directly proportional to the radius of sphere irrespective of time. In the graph, the different non-dimensionalised time has been chosen in which the starting and end point i.e 0 and 1, the ice thickness increases with the increase in radius of sphere following up curve as shown.

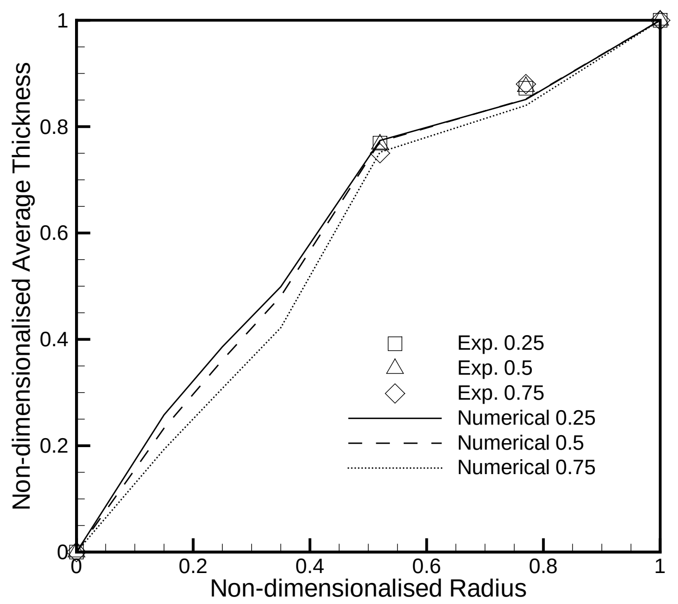


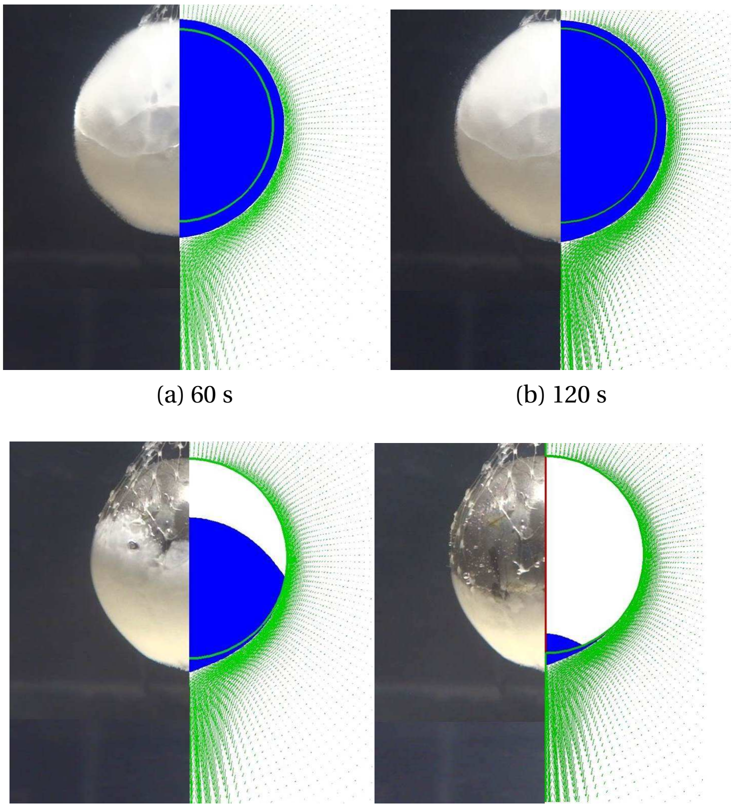
Figure 2.11: Graph showing non dimensionalised radius vs non dimensionalised average thickness of ice formed

2.3.2 Numerical Results

The set of governing equations above is solved numerically for an 2d axisymmetric case. The numerical results are compared with the experimental results in the following sections.

2.3.2.1 Comparison of Experimental and Numerical Results

The overall process of solidification and melting of water for 4.14cm sphere is compared in figure 2.12. The left part of figure shows experimental result and the right side shows numerical result at different time instances. The ice thickness formed at different time instances are almost similar for both the cases. In this figure the shaded portion indicates the portion of sphere which is below 0^oC. The ice layer formed in both the cases can be clearly seen. It can be noticed that during the solidification process, the ice layer grows is almost symmetric (till =120s). After that uneven melting take place, as stated earlier, this uneven melting can be clearly seen in figure2.12 (c) and (d). When the sphere size is reduced by almost half i.e 3.18cm, the surface area decreases by almost four folds.



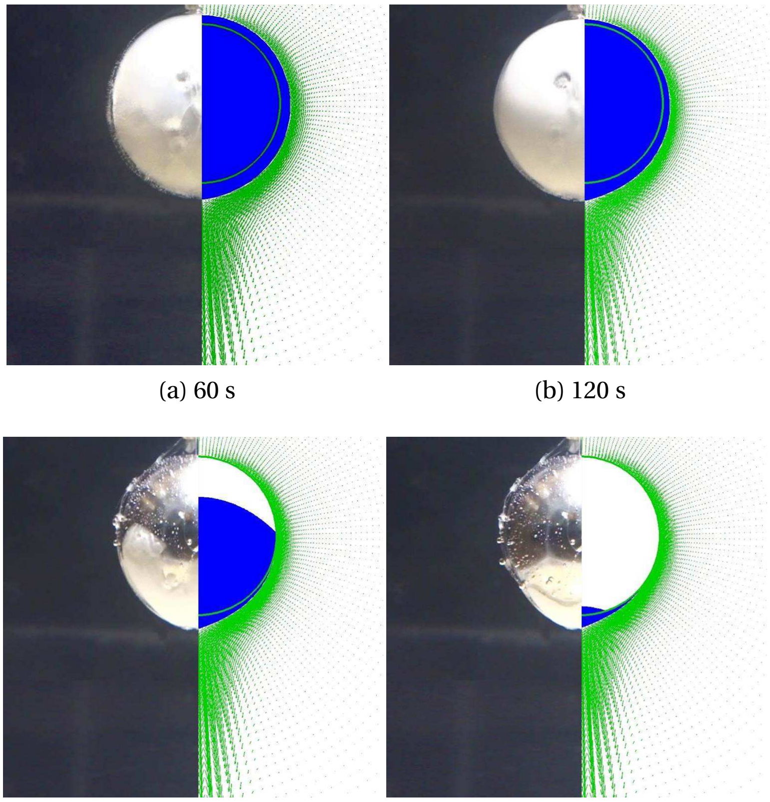
(a) 60 s (b) 120 s

(c) 240 s (d) 280 s

Figure 2.12: Ice profile comparison for 4.14 cm sphere

The decrease in surface area reflects in less solidification which is visible in figure 2.13. Because of the less driving force for the solidification, melting starts much earlier compared to the previous case of bigger sphere. At t = 180s, almost half of the frozen ice melted and a good matching numerical and experimental results can be seen in figure 2.13(c). For this case, all the ice melts at t = 210s. Similar trend is also noticed for the smaller sphere, i.e. 2.72cm (see figure 2.14). For this case, almost half of the ice is melted at t =150s and complete melting takes place at t = 180s.

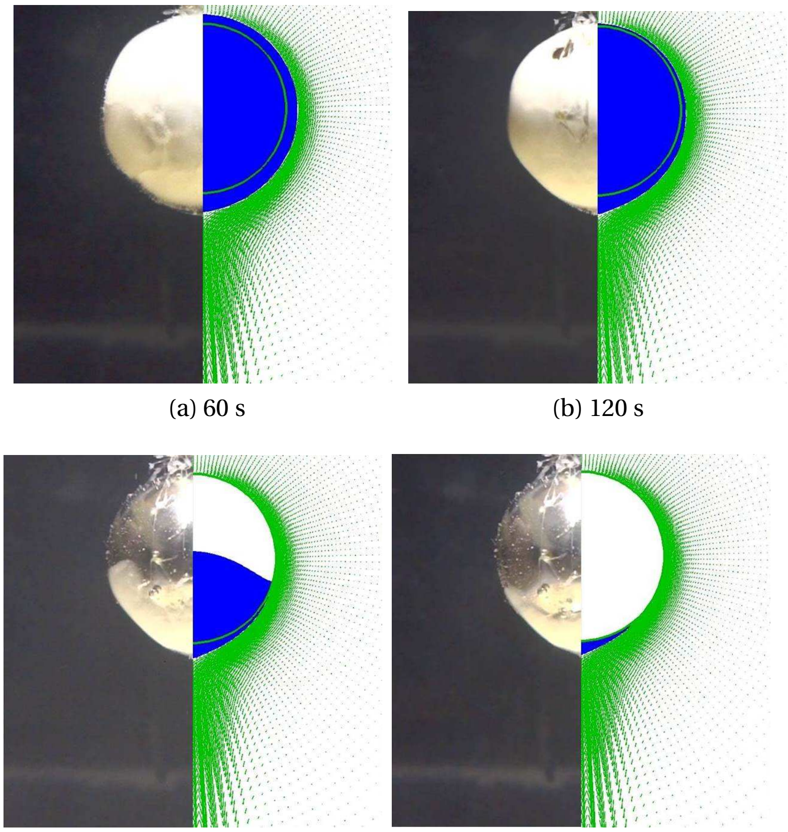
The ice thickness have been measured at top, bottom and center surface of different sizes of sphere. The result is presented graphically in which the solidification and melting curve follows same trend at top, bottom and center surface irrespective of sizes of spheres. The Bottom surface is having more thicker ice layer compared to other two surfaces due to buoyancy driven convection effect. This trend is almost same as of experimental result that is obtained. The solidification is very fast due to high cooling rate which is itself the result of cryocooled sphere. The graph shown represents the time and



(a) 60 s (b) 120 s

(c) 180 s (d) 190 s

Figure 2.13: Ice profile comparison for 3.18 cm sphere



(a) 60 s (b) 120 s

(c) 150 s (d) 160 s

Figure 2.14: Ice profile comparison for 2.72 cm sphere

thickness variation in non-dimensionalised form. Here also the solidification curve is more steeper than melting curve so it take place very fast but melting takes longer time. This solidification and melting of ice is similar to experimental result, Their is small time range where the ice thickness remains constant and after that only the melting starts. Due to some human errors the graph may vary but it is very less. Thus with this also the volume of ice formed during different time aspects can be calculated directly. So only thickness has been shown here which similar to the experimental results.

The flow field can be seen for each case at different time instants. The flow of water during solidification and melting is due to buoyancy driven force. As the difference in diameter of spheres are not that large and the other parameters like temperature difference, fluid etc. remain same, the developed flow field is nearly same for all cases. It is laminar flow, so the separation zone is not visible, the water flows very close to the wall of ice formed. From figures the direction of flow field is visible. The fluid moves from top to bottom due to buoyancy driven natural convection. The size of the arrows shows the magnitude of strength of flow; the longer the arrow, higher is the magnitude. The density of arrow shows which part is having more strong flow field. The strong flow is always very near to the surface of ice formed during solidification and also during melting.

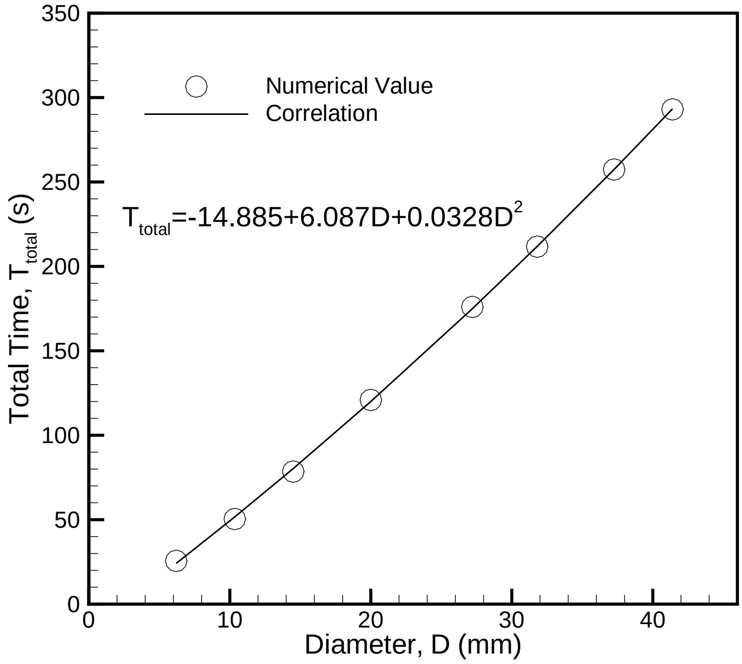


Figure 2.15: Correlation between total time and diameter of sphere

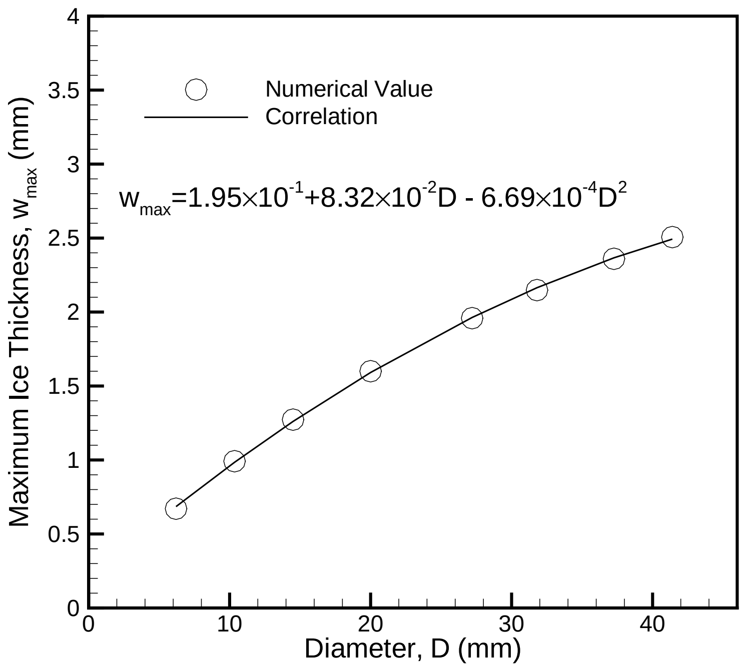


Figure 2.16: Correlation between maximum ice thickness and diameter of sphere

2.3.2.3 Correlations

The curves obtained with experimental results are almost matching with the numerical results. So, by using numerical values, correlations have been introduced between time-diameter of the sphere, and between max ice thickness-diameter of the sphere as shown in figure 2.15 and figure 2.16.

These correlation are having a goodness fit of more than 99.99%. From the curve fit shown in figure 2.15, an equation is obtained with which the total time i.e T_{total} required for the solidification and melting can be found for any diameter of sphere. Similarly, from figure 2.16, maximum ice thickness i.e. w_{max} can be found for any diameter of sphere. The equations are shown below:

$$T_{total} = -14.885 + 6.087D + 0.0328D^2$$

$$w_{max} = 1.95 \times 10^{-1} + 8.32 \times 10^{-2} D - 6.69 \times 10^{-4} D^2$$

CHAPTER 3

Conclusion and Future work

The Experimental and Numerical analysis is performed for solidification and melting of water around cryocooled sphere. The following conclusions can be drawn out :

1. Solidification and Melting of water follows same trend irrespective of the sizes of sphere. The solidification curve will always be steeper compared to melting curve and will also take more time to melting compared to solidification.

2. The thickness of ice formed at the bottom is always more compared to other portion irrespective of the size of sphere. This is due to Buoyancy-driven natural convection effect which is weaker during solidification but becomes stronger during melting.

3. The ice thickness always increases at different time instants along with increase in radius of sphere except at starting of solidification and end of melting.

4. The changes in the flow field is nearly negligible, due small variation in radius of sphere. But if the larger radius sphere is chosen, variation in flow field can be easily seen. Due to higher cooling rate, the natural convection current grows more stronger.

In future, the spheres of different materials having remarkable difference in thermal conductivity can be performed to find out the relation between thermal conductivity of metal spheres and ice thickness so that it will be easier to find out the material which will be effective to obtain larger amount of ice.

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